

## **RF MEMS Switch with Integrated Impedance Matching Structure**

### **Cross Reference to Related Application**

This application claims the benefit of US Provisional Patent Application No. 60/470,026 filed May 12, 2003, the disclosure of which is hereby incorporated herein by reference.

### **Technical field**

The presently disclosed technology relates to RF Micro-Electro-Mechanical System (MEMS) switches and, more particularly, to RF MEMS switches with integrated impedance matching structures.

### **Background Information**

Return loss is a measure of the amount of energy reflected back toward the RF source by a device. A high return loss (in dB) means that most of the signal energy gets into the device, or for a switch, most of the energy gets through the switch, if the switch itself has very little insertion loss. This is important for RF receiver front-ends where any loss, including loss of energy by reflections, directly impacts the gain and noise figure of the system.

The current HRL Laboratories' double-contact RF MEMS shown in Figure 1 has a return loss that is less than 15 dB at 40 GHz when the switch is closed. This is too low for many switch networks where a return loss of greater than 20 dB is desired. An embodiment of the RF MEMS switch described herein is an improved double-contact RF MEMS that can achieve a return loss better than 30 dB with 3 dB or less degradation of isolation. This is an improvement of at least 15 dB in return loss over the current HRL Laboratories' practice.

Having a high return loss is important in any electrical system. HRL Laboratories' RF MEMS switch designs have been considered for use in a number of applications, including low-loss phase-shifters, system redundancy, millimeter wave beam switching, and tunable filters and oscillators. Improving the return loss, by increasing it, is desirable.

The prior art includes:

1. Loo, et. al., "Fabrication of Broadband Surface Micromachined Micro-electro-mechanical Switches for Microwave and Millimeter Wave Applications," US Patent No. 6,331,257 of December 18, 2001. This patent identifies the equivalent circuit of HRL Laboratories' switch as inductive in nature and that shunt capacitances could be used as impedance matching circuits for the switch. Figure 6 of this patent shows such a matching network using microstrip radial stubs. Microstrip radial stubs are elements well known for impedance matching circuits, but they are not necessary, and perhaps overly complicated, for a monolithic matching circuit.

2. Loo, et. al., "Monolithic Single Pole Double Throw RF MEMS Switch," US Patent No. 6,440,767 of August 27, 2002. The current practice of HRL Laboratories' RF MEMS double contact switches uses an elongate, moveable metal bar to connect the input and output transmission lines when the switch is closed. This metal bar has a width that is less than the width of the input and output transmission lines. The input and output transmission line width is nominally 50 ohms when the switch is used in a series microstrip configuration. Although some switches in the past have been fabricated with a bar the same width as the input and output transmission lines, the preferred practice is now to fabricate switches with a narrow connecting bar. This is because of fabrication yield and insertion loss reliability when the switch is closed. This type of switch is shown in the figures of that patent.

In order to make the transition from the larger width line to the smaller width line, a short linear taper is used. The metal bar appears as a small inductor at frequencies where its length is much less than a wavelength. When the taper and metal bar are much less than a wavelength, the effect of the inductance is not noticeable and the return loss is very good. As the frequency increases, the inductance of the bar becomes significant, and the return loss degrades.

With respect to this technology, the inventors have taken into account the inductance of the metal bar, and have added integrated compensating capacitors to the electrode itself. These capacitors take the form of a widening or hump in the input and output lines close to the switch connection bar contacts in combination with the switch's ground plane. This results in a vast improvement in the return loss of the switch with the narrow metal connecting bar, especially at millimeter wave frequencies.

Aside from the patents listed above, documents related to other tapered structures related to monolithic circuits and switches are noted below which shows that most switch devices are capacitive in nature, thus requiring inductive matching such as tapered lines. Being inductive, HRL Laboratories' RF MEMS switch is apparently unique in the field of RF switches in that it requires a capacitive-type matching network.

1. Malherbe, A. G. Johannes and Steyn, Andre F., "The Compensation of Step Discontinuities in TEM-Mode Transmission Lines," *IEEE Trans. Microwave Theory Tech.*, Vol. MTT-26, No. 11, November 1978, pp. 883-885. - The use of short tapers between transmission line step discontinuities is a standard practice for microwave devices, such as diodes and FET's. In most cases, the input to the device has a parasitic capacitance, so narrowing the input transmission line adds some compensating inductance. Since the active part of the device is very small compared to a wavelength, linear tapers provide an acceptable input to and output from the device. This paper shows how to optimize this transition. This paper is listed to help give a physical basis to the current practice of RF line connection to microwave devices.

2. Jablonski, W., Jung, W., Gorska, M., Wrzesinska, H. and Zebrowski, Z. "Microwave Schottky Diode With Beam-Lead Contacts," 13th International Conference on Microwaves, Radar and Wireless Communications. 2000, *MIKON-2000*, Vol. 2 , pp. 678-681, 2000. And Maruhashi, Kenichi, Mizutani, Hiroshi, and Ohata, Keichi, "Design and Performance of a Ka-Band Monolithic Phase Shifter Utilizing Nonresonant FET Switches," *IEEE Trans. Microwave Theory Tech.*, Vol. 48, No. 8, August 2000, pp. 1313-1317. - Both of these papers have figures which show a linear taper from microstrip transmission line inputs and outputs into the device active region. These papers are cited as examples of current practice.

3. Rebeiz, Gabriel M. and Muldavin, Jeremy B., 'RF MEMS Switches and Switch Circuits,' *IEEE Microwave Magazine*, December 2001, pp. 59-71. - This paper has a figure that shows that even for series RF MEMS, linear tapers are used to connect to the switch region.

### **Current Practice and Background Information**

Figure 1 shows a drawing of a RF MEMS switch according to a current practice of HRL Laboratories of Malibu, California. The switch is fabricated on a substrate 1 such as semi-

insulating GaAs or other high resistivity material. The switch is comprised of a cantilever beam 2 that is fabricated from silicon nitride and gold, as described in U. S. Patent No. 6,440,767. This cantilever beam is pulled down by an electrostatic force between two actuation electrodes 3. The voltage required for actuation is supplied from an external source through actuation electrode pads 4, and metal lines 5 connecting the pads 4 to the actuation electrodes 3. RF transmission lines 6 are also fabricated on the substrate 1. Lines 6 are not connected together so that when the cantilever beam 2 is in its up position, a gap exists between the RF lines 6 and an RF open circuit exists between the RF input and output. When the cantilever beam 2 is pulled down, an elongate moveable metal member or bar 7, which is part of the cantilever beam, is brought across the RF lines 6, connecting them together, thus connecting the RF input and output. The actual metal contacts to the RF transmission lines 6 are provided by two metal dimples (not shown in this figure) that are fabricated as part of the contact bar 7. The bar 7 preferably provides high contacting pressure for low contact resistance at the metal dimples. A ground plane is provided on the bottom side of the substrate 1.

The width of the metal contacting bar 7 is optimized for fabrication yield as well as low contact resistance. The widths of the RF transmission lines 6 are made to be  $50\ \Omega$  at the edges of the switch when the bottom of the substrate 1 is grounded (in this case the transmission lines are known as microstrip lines). As shown in Figure 1, the metal bar 7 is smaller in width than the input and output RF transmission lines 6. Two tapered regions transition the RF lines to the smaller width of the contact bar 7 and dimples. In general, the use of transmission line tapers can be found in prior art for connection to high frequency devices as described above.

The measured insertion loss of the switch in Figure 1 is typically 0.25 dB or less up to 40 GHz, and the measured isolation is approximately 25 dB or better up to 40 GHz. The measured return loss is typically 15 dB or better up to 40 GHz. In many applications, especially when the switch is used near a receive antenna, the desired return loss is specified to be greater than 20 dB in order to prevent back-reflections from coupling over to nearby elements, particularly in antenna arrays. The current switch of Figure 1 does not meet this specification at millimeter wave frequencies. This disclosure teaches how to design a switch with integrated impedance matching structures that can provide better than 20 dB return loss at 40 GHz and still maintain better than 20 dB isolation.

The contacting bar 7 of the switch behaves as a small series inductor. For example, a microstrip line that is  $26\ \mu\text{m}$  wide and  $100\ \mu\text{m}$  long, which are the dimensions of the contacting bar of many of HRL Laboratories' RF MEMS switches, has an equivalent circuit inductance of 34

pico-henries. This was calculated using Eagleware Genysis™ microwave circuit design software, where the microstrip line was assumed to be on a GaAs substrate 100 μm thick.

As is disclosed herein, from a circuit perspective, this inductance of the contacting bar 7 can be matched out by utilizing small shunt capacitances, each 6.8 fF forming a  $\pi$ -network with the switch contacting bar 7. An equivalent circuit is shown in Figure 2 along with the calculated return loss (again using Eagleware Genysis™) is shown in Figure 3. Of course, the resulting switch itself is more complicated than this simple circuit model, but this field simulation software was utilized to verify that an impedance matching structure might well be integrated into the design of a MEMS switch.

### **Brief Description**

In one aspect, the presently disclosed technology provides an impedance matching structure for a RF MEMS switch having at least one closeable RF contact in a RF line, the impedance matching structure comprising a protuberance in the RF line immediately adjacent the RF contact.

In another aspect, the presently disclosed technology provides an impedance matching structure for a RF MEMS switch formed on a substrate, the switch having two closeable RF contacts, a first of the two closeable RF contacts being coupled to a first RF line disposed on the substrate and a second one of the two closeable RF contacts being coupled to a second RF line disposed on the substrate, and an elongate moveable bar for closing a circuit between the two closeable RF contacts, the impedance matching structure comprising a first protuberance disposed on the substrate in the first RF line immediately adjacent the first one of the two closeable RF contacts and a second protuberance disposed on the substrate in the second RF line immediately adjacent the second one of the two closeable RF contacts.

In yet another aspect, the presently disclosed technology provides a method of increasing the return loss of a MEMS switch to a level greater than 20 dB. The method includes selecting a MEMS switch arranged on a substrate and whose reactance is inductive; and then adding small capacitors on the substrate, each capacitor having two elements, a first element of each capacitor being formed by a protuberance or hump formed in RF lines disposed on the substrate and coupled to RF contacts associated with the MEMS switch, the protuberance or hump in each RF line being arranged immediately adjacent an associated RF contact and a second element of each capacitor being provided by a ground plane associated with the MEMS switch.

## **Brief Description of the Drawings**

- 5     Figure 1 depicts a prior art RF MEMS switch designed by HRL Laboratories;
- Figure 2 is an approximate equivalent circuit of the switch-contacting bar of Figure 1;
- Figure 3 is a graph of the calculated return loss up to 40 GHz of the switch of Figure 1;
- 10     Figure 4 depicts an embodiment of the impedance matching structure for a RF MEMS switch in accordance with the presently disclosed technology;
- Figure 5 is a graph of the calculated return loss and isolation at 40 GHz as a function of tapered
- 15     section end width;
- Figure 6 is a graph of the calculated insertion loss of the linear taper section impedance matched switch as a function of frequency with the taper section end width as a varied parameter;
- 20     Figures 7a and 7b depict another embodiment of the impedance matching structure for a RF MEMS switch that was modeled on HFSS software for optimum insertion loss and with better isolation performance than the embodiment of Figure 4 (Figure 7b is a more detailed view of the impedance matching structure of the switch having dimensions stated thereon in  $\mu\text{m}$ );
- 25     Figure 7c is an elevation view of the embodiment of Figures 7a and 7b showing the cross bar and dimples in greater detail;
- Figure 8 depicts another embodiment of the impedance matching structure for a RF MEMS switch structure, this embodiment having wide RF transmission line protuberances or “humps”
- 30     (the width being 216  $\mu\text{m}$  in this figure);
- Figure 9 is a graph of the calculated return loss and isolation at 40 GHz as a function of RF line hump widths for the embodiment of Figure 8;
- 35     Figure 10 is a top view of a single-contact RF MEMS switch geometry with impedance matching humps (dimensions are indicated in  $\mu\text{m}$ ); and

Figure 11 is a graph of the calculated return loss and isolation at 40 GHz of the single-contact RF MEMS switch shown in Figure 10 as a function of matching circuit hump width.

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### Detailed Description of the Preferred Embodiments

10 An embodiment of an impedance matching switch is shown in Figure 4. This switch represents an improvement over the switch shown in Figure 1. Nevertheless, common reference numbers are used to refer to common elements for ease of explanation and understanding.

15 Figure 4 shows a configuration of the impedance-matched switch that was used for simulation of the switch using Ansoft HFSS™ field software. The switch substrate chip 1 was assumed to be 100 micron thick GaAs that is 400  $\mu\text{m}$  wide by 700  $\mu\text{m}$  long. The dimensions of the actuation electrodes, pads, and cantilevers are identical to that of Figure 1, and in fact, these dimensions represent one of the current practice switches fabricated at HRL Laboratories of Malibu, California.

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The RF transmission lines are preferably 70  $\mu\text{m}$  wide at the edges 9 of the chip, to provide a 50 $\Omega$  characteristic impedance, which is preferred for many applications, on the 100 micron thick GaAs substrate 1. The impedance matched switch includes protuberances 15, which are each defined, in this embodiment, by a tapered section or portion 10 in the RF lines 6 which begins, at 25 numeral 11, 82  $\mu\text{m}$  from the edges 9 of the chip (of course, other starting points could be used for the beginning point of the taper) and which varies preferably linearly in width to a point 12 that is preferably directly lateral of the start of the dimple contacts 14 associated with the cross bar 7. The protuberances 15, in this embodiment, include a straight section 13 that is preferably equal in length, in this embodiment, to the length of the dimple contacts 14 and which extends 30 parallel to the edge of the RF lines 6 immediately adjacent dimple contacts 14. The boundaries of each protuberance 15 is then preferably completed by another preferably straight line section 17 which mates the straight section 13 with the associated RF line 6 next to the associated dimple contract 14.

35 The contact resistance of the dimples 14 was simulated by assuming the resistivity of the dimple metal 14 to be 0.5  $\Omega$  resistance per dimple 14. The dimples can be disposed on the cross bar 7

and/or on the RF lines 6 as shown in Figure 7c, but preferably on the cross 7 as shown by the solid line rendition in Figure 7c. A ground plane 18 is preferably provided on the bottom side of the substrate 1.

- 5 The tapered section, which begins at numeral 11 and extends outwardly to point 12, helps define a protuberance or “hump” 15 at the end of each of the RF lines 6 immediately adjacent the dimple metal contacts 14 that make contact with the RF lines 6 of the switch when the switch is closed.
- 10 Simulation of the insertion loss, return loss, and isolation was performed with the taper end width or hump width 16 varying from 26  $\mu\text{m}$  to 130  $\mu\text{m}$ . The results of this simulation are shown in Figures 5 and 6. Figure 5 is a plot of return loss and isolation at 40 GHz. From that figure, it can be seen that the return loss of the switch is greater than 20 dB for a taper end width of greater than 90  $\mu\text{m}$ . The isolation, which was calculated from the model with the switch open such that
- 15 the dimple contacts were 2  $\mu\text{m}$  above the RF line, degrades about 3 dB at an end width of 90  $\mu\text{m}$  compared to an end width of 26  $\mu\text{m}$  for this embodiment. Figure 6 shows the insertion loss as a function of frequency with the taper end width as a parameter. Improvement in the return loss also improves the insertion loss, especially at higher frequencies.
- 20 The reduction in isolation occurs from the increased fringing field due to the widened RF line 6 protuberance or hump 15 at the dimple contact 14 region. The isolation of the switch can be improved, while still maintaining excellent impedance matching, with the embodiment shown in Figures 7a and 7b. In this embodiment, the boundaries of the impedance matching structures 15 include two portions of increased line width (leading to predominantly shunt capacitive matching
- 25 sections), forming protuberances or humps 15 on the input and output transmission lines. Compared to the embodiment of Figure 4, the boundary of each protuberance or hump 15 in this embodiment has two tapered sections: a first tapered section begins at point 11 as in the case of the first embodiment, but after the protuberance or hump 15 has reached its maximal width, it decreases in width along a second tapered portion 17'. In Figure 3 section 13 had a constant
- 30 width, while in the present embodiment, section 17' has a decreasing width towards contacts 14.

Figure 7b shows this embodiment in greater detail. The RF lines 6 are preferably 70  $\mu\text{m}$  wide and the hump width increases to a 100  $\mu\text{m}$  width at the humps 15. Figure 8 shows an embodiment with RF lines 6 having even larger protuberances 15 - in this embodiment the RF

35 lines have a maximal hump width of 216  $\mu\text{m}$  at the protuberances 15 (compared to the 100  $\mu\text{m}$  width for the embodiment of Figure 7a and 7b). The dimple contact 14 width is still 26  $\mu\text{m}$  for



these embodiments and a linear line taper leads from the widest portion of the protuberance 15 back to the region where the dimple contact 14 is located. Field simulations show that for the embodiments of Figures 7a/7b and 8, the optimum impedance match at 40 GHz occurs when the hump 15 is 186  $\mu\text{m}$  wide (which is then 186/70 or slightly more than 2.5 times the width of the RF line 6). This is graphed in Figure 9, which also shows the calculated isolation values, for different protuberance or hump widths 16. In that graph it can be seen that a 35 dB return loss can be achieved with 22 dB isolation, compared to 26 dB return loss and 20 dB isolation for the embodiment of Figure 4 (the simulations of the embodiment of Figure 4 set forth in Figure 5 were not run out to the optimum return loss, but the trend in the calculated isolation values would only get worse at the optimum return loss).

Figure 7c shows this embodiment as an elevation view taken along line 7c shown in Figure 7b.

As such, the embodiments of Figures 7a, 7b and 8, where the boundaries of the protuberances 15 each include two tapered straight line sections, appear to be superior to the embodiment of Figure 4. It is believed that additional straight line sections in the boundaries of the protuberances 15 would also provide very satisfactory results as would the use of a curved protuberance such as the curved line boundary P in Figure 7b which approximates the straight line boundary defined by edges 10, 13 and 17.

A similar impedance matching protuberance or hump 15 for an embodiment of a single contact switch is shown in Figure 10. Figure 11 shows the plot of simulated return loss and calculated isolation values versus hump 15 width for the embodiment of Figure 10. The widths of the RF lines 6 are preferably 70  $\mu\text{m}$  while the width of the cross bar 7 is preferably 26  $\mu\text{m}$ . From Figure 11 it can be seen that the return loss is better than 25 dB over a hump width range from 140 to 200  $\mu\text{m}$ , thus the return loss optimization is less sensitive to the impedance matching network than the double contact switch embodiments of Figures 4 and 7a/7b. Also, the isolation changes by about 1 dB (it actually improves) as the protuberance or hump 15 width 16 is varied.

In the foregoing embodiments, the impedance matching protuberances or humps 15 are shown typically with one (see element 10) and preferably two (see elements 10 and 17') straight line tapered sections that are disposed at neither 0° nor 90° to the immediate straight line edges of the RF lines 6. These tapered sections 10, 17' effectively increase the width of the RF lines 6 in the immediate vicinity of the switch bar 7 contacts 14. The tapered sections 10, 17' need not necessarily be defined by straight lines. For example, it is believed that rounded humps or protuberances 15 (see line P in Figure 7b) or humps or protuberances formed by a series of

shorter straight line sections will also prove quite satisfactory.

Having described this technology in connection with certain preferred embodiments,  
modification will now doubtlessly suggest itself to those skilled in the art. As such, the presently  
5 disclosed technology is not to be limited to the disclosed embodiments except as required by the  
appended claims.